Final Report for "The Dynamical Mechanisms and Potential Predictability of Indian and Pacific Ocean Influences on Seasonal North American Drought'"

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1. Project goal

The main goals of the project were:

1. Develop a more comprehensive understanding than available to date of how tropical Pacific and Indian Ocean SST anomalies can impact North American precipitation and drought.

2. Determine what matters in the SST anomalies, what the strength of the relations are, how this depends on season.

3. Determine the physical mechanisms that couple the mean and transient atmospheric circulation, the moisture budget and precipitation.

2. Geographical location of study

Work was conducted in the U.S. and focused on precipitation and variability over North America/

3. Partners

None, other than co-authors from outside Columbia University.

4. Decision-makers/end-users

Not applicable.

5. Matching funds/leverage

None

6. Research objectives

As for Project goal.

7. Research approach and methodology

The work rested on the development of a library of ensembles of atmosphere model simulations with idealized and real world SST forcings that were used to determine how SSTs influence US drought and precipitation as a function of location and season. The modeling results were used to examine particular events, most notably the California drought and El Niño of winter 2015/16 as well as more general relations. Below we provide detailed summaries of the results of our work.

8. Accomplishments: Research findings

a. Causes and predictability of the 2011/14 California drought

The PI was the lead author of the DTF report on the causes and predictability of the California drought and coordinated research by Lamont, IRI, NOAA ESRL and NOAA CPC and NASA GSFC using analyses of observations and 7 large ensemble simulations with different atmosphere models forced by historical SSTs. The report was then converted into a *Journal of Climate* paper. Results presented are as follows. Historically, dry California winters are most commonly associated with a ridge off the west coast but no obvious SST forcing. Wet winters are most commonly associated with a trough off the west coast and an El Niño event. These attributes of dry and wet winters are captured by many of the seven models. According to the models, SST forcing can explain up to a third of California winter precipitation variance. SST-forcing was key to sustaining a high pressure ridge over the west coast and suppressing precipitation during the three winters. In 2011/12 this was a response to a La Niña event whereas in 2012/13 and 2013/14 it appears related to a warm west, cool east tropical Pacific SST pattern. All models contain a mode of variability linking such tropical Pacific SST anomalies to a wave train with a ridge off the North American west coast. This mode explains less variance than ENSO and Pacific decadal variability and its importance in 2012/13 and 2013/14 was unusual. The CMIP5 models project rising greenhouse gases to cause changes in California all-winter precipitation that are very small compared to recent drought anomalies. However, a long term warming trend likely contributed to surface moisture deficits during the drought. As such, the precipitation deficit during the drought was dominated by natural variability, a conclusion framed by discussion of differences between observed and modeled tropical SST trends.

Figure 1 shows a summary plot for the analysis. The top panel shows the anomalies of observed SST (colors over the ocean), precipitation (colors over land) and 200mb heights (contours) averaged over the November to April winter half years of 2011/14. The warm west-cool east tropical Pacific pattern is seen and which we believe is critical for forcing the wave pattern that created the west coast ridge which is also seen together with the pan-west coast drought. The lower panel shows the average of the seven model ensemble means and makes clear that, when forced by the observed SSTs, the models can reproduce the west coast ridge and dry conditions, albeit weaker than occurred in nature. (Note the SSTs are not quite the same in the two panels due to the models using slightly different products - see below.)

b. Diagnosing the SST forcing component of the current California drought

In our work examining the causes of the multiyear California drought we identified an important, though seemingly not dominant, role for forcing by tropical Indo-Pacific SST anomalies (Seager et al. 2014 NOAA DTF Report, Seager et al. 2015 J. Climate). In this past year we have examined this more using the methodology of idealized, imposed SST anomalies as described in the proposal. Using a library of idealized SST forcing experiments we identified the linear combination of SST forcings that drive an atmospheric circulation anomaly that best matches (via an optimization procedure) the observed circulation anomaly during winter 2013/14 which was the driest winter of the drought. Despite the ability to come up with all manner of ways to create a west coast ridge, this optimization procedure decides that warm SST anomalies in the tropical west Pacific are ideal. The optimized SST, precipitation and divergent circulation anomalies are decidedly similar to those that actually occurred during winter 2013/14. This work, therefore adds to other work (by us an also by MAPP and DTF colleagues, Teng and Branstator, and by the Oxford University group led by Tim Palmer) that indicates that tropical SST anomalies that are distinct from those during peak ENSO events played an important role in generating the drought. Our optimization methodology suggests that the SST anomalies made a west coast ridge like that in winter 2013/14 2 to 3 times more likely than internal atmosphere variability alone could generate (see Figure 2). This was published in Seager and Henderson (2016, J. Climate).

c. The role of temperature variability and change in the current California drought

Reviewers of the DTF report (four) and the *J. Climate* paper (three more) all brought up the issue of the role of temperature in the California drought. While that was addressed in the *J. Climate* paper, we felt compelled to examine it in more detail. We published (Williams et al. 2015), an exhaustive analysis of California Palmer Drought Severity Index using the Penman Monteith method for computing potential evapotranspiration and using all available combinations of precipitation and temperature data (yes, really). The PDSI was then computed using, first, actual and, second, climatological precipitation and temperature to work out, from a surface moisture perspective, the relative contributions of precipitation and temperature to the California drought. 75-80% of the PDSI-measured drought was due to the drop in precipitation, explained by Seager et al. (2015), and the remainder was due to the warm temperatures. The temperature effect was then decomposed into components due to variability (i.e. the same ridge that was blocking the storms) and radiatively forced trend. The long term trend is providing a steady increase in drought stress such that the same precipitation drop is combining to create worse soil moisture conditions than in prior decades.

d. El Nio impacts on US precipitation and the case of the 2015/16 El Nio

In 2016 we published a paper that advanced our understanding of the physics of how El Nio impacts US precipitation, focusing on California and the southwest. The mystery was why, as the El Nio SST anomalies weaken from early to late winter (from NDJ to FMA), the atmospheric circulation anomaly and precipitation anomaly over the southwest strengthens. It was found that this was related to the seasonal cycle of mean SST in the eastern equatorial Pacific (EEP) cold tongue: as the cold tongue warms from winter to spring, a diminishing warm SST anomaly can cause an increase in the total SST and a spread of convection to the east and driving of a powerful teleconnection that creates westerly flow and an enhanced storm track at the southwest coast of North America. In the newest work, we note that almost all models forecast SST anomalies that stayed too warm too long in the EEP. We used atmosphere models to show that this SST forecast bias led to a modest wet bias in the California precipitation forecast (see Figure 2). However, this alone cannot explain the difference between the precipitation forecast and the actual, near to normal, conditions that occurred in California in the El Nio winter of 2015/16. This paper (Jong et al. 2017) is in review at J. Climate, reviews have been received and the paper is being revised.

e. Changing patterns of SST and influence on winter circulation and precipitation anomalies across western North America.

We have used our methodology of examining the model atmosphere responses to idealized SST anomalies to examine the possibility of whether climate change is making dry winters at the North American west coast more likely. The CMIP5 ensemble cannot be used to make this case. We analyzed the individual runs of all CMIP5 models and found that the climatological means shift towards a trough off the west coast and higher winter precipitation at the coast from central California north and also thatr the extremes do not increasingly favor a ridge/dry state. However, the observed climate has been trending over past decades to a ridge at the west coast, in contrast to the CMIP5 models. This trend has been associated with a trend towards a warm/cool western/eastern tropical Pacific Ocean that is akin to the state associated with the California drought. The idealized SST modeling work, based on optimizing for the pattern of the height trend, indicates that a warm/cool west/east tropical Pacific is optimal for generating a west coast ridge. This work allows a case to be made that increasing greenhouse gases are forcing a tropical SST response pattern that can drive a tendency towards a west coast ridge. This work is in review at J. Climate (Seager et al. 2017).

f. Pan-coastal and dipole modes of precipitation variability at the west coast

It is widely assumed that the dominant mode of winter precipitation variability at the west coast is a northwest/southwest dipole associated with ENSO and the PDO. We revisited this and found that actually, the leading mode is a pan-coastal one in which, for example, winter precipitation in Seattle and Los Angeles vary in phase. The dipole mode is a second mode that explains less of the total variance. Pan coastal droughts appear primarily tied to internal atmosphere variability while the dipole mode is linked to tropical Pacific SSTs that control the latitudinal location of the jet and storm track. The dipole mode, of course, has potential predictability that will be challenging for the pan-coastal mode. However, the pan-coastal mode has significant social impact because, as in recent years, it has created wildfires that extend from Mexico to Canada and place massive stress on USFS budgets and resources. This paper (Cook et al. 2017) is in review at J. Climate.

g. Mechanisms and SST-based predictability of North American drought

We have published a paper that reviews the state-of-the art in predicting North American drought on annual to decade timescales. The paper first reviews the physical mechanisms that connect SST anomalies in the tropical Pacific and North Atlantic to precipitation and temperature over North America. It then reviews recent progress on prediction of the relevant SST anomalies on the annual to decade timescale. The paper concludes that there is reason for optimism that both tropical Pacific and tropical North Atlantic SST anomalies have some predictability beyond the seasonal timescale and efforts are justified to determine if this can be translated into useful prediction of precipitation and temperature over North America (Seager and Ting, 2017, Curr. Clim. Ch. Rep.)

h. Inter-model comparison of SST-forcing of North American drought

To date most of our work examining the tropical SST controls on drought over North America has used the NCAR CCM3 model. We have conducted an extensive comparison of the realism of these teleconnections in CCM3 compared to later NCAR models and found that by many metrics CCM3 performs better, despite its 1998 vintage. We are now developing a 16 member, 1856 to 2016 ensemble of SST-forced simulations with the new NCAR CAM5.3 model. We have also used CAM5.3 in our examination of winter 2013/14 and simulations of circulation and precipitation sensitivity to different estimates of SST states. This new modeling work will allow us to assess if the realism of North American drought - tropical SST connections is improved in CAM5.3 relative to the vintage CCM3. Using CAM5.3 comes at a considerable cost since, for the same spatial resolution, it uses five times the computer time, so serious assessment of the trade offs between simulation realism and the number of numerical experiments that can be performed need to be made. All model simulations are available as a community resource.

9. Accomplishments: Outreach and communication activities

The lead PI attended the National Integrated Drought Information System meeting in Sacramento, CA, and talked about the California drought to stakeholders during the drought (May 2014).
The DTF report on the California drought was released with a press conference featuring the lead PI.
The lead PI gave a briefing on prospects for improved drought prediction to Congressional staff members, January 2015.
Lamont and Columbia created a video describing our work on the California drought `https://www.ldeo.columbia.edu/video/richard-seager-sees-hand-climate-change-drought`

10. Accomplishments: measuring impact on decision-making

Not applicable.

11. Accomplishments: Deliverables produced

Other than research publications we led the Drought Task Force report: "Causes and Predictability of the 2011-14 California drought" and also the Drought Task Force bulletin "What can drought-striken California expect from the upcoming El Nio winter?".

12. Significant deviations from proposed workplan

None too significant.

13. Publications

1. Cook, B. I., A.P. Williams, J.S. Mankin, R. Seager, J.E. Smerdon and D. Singh, 2017: Revisiting the leading drivers of Pacific coastal drought variability in the contiguous United States, J. Climate, 31: 25-43, doi:10.1175/JCLI-D-17-0172.1. http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/CookEtAl2018JC.pdf

2. Jong, B.-T., M. Ting, R. Seager N. Henderson and D.-E. Lee, 2017: Role of equatorial Pacific SST forecast error in the late winter California precipitation forecast for the 2015/16 El Niño, J. Climate, 31: 839-852, doi: 10.1175/JCLI-D-17-0145.1. http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/JongEtAl2018JC.pdf

3. Jong, B., M. Ting and R. Seager, 2016: El Nio's impact on California precipitation: Seasonality, regionality and El Niño intensity. Env. Res. Lett., 11: doi:10.1088/1748-9326/11/5/054021. http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054021/pdf

4. Seager, R; M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, N. Henderson, 2015: Causes of the 2011-14 California Drought, J Climate, 28(18): 6997-7024, DOI: 10.1175/JCLI-D-14-00860.1.
http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/SeagerEtAl20152011_14.pdf

5. Seager, R; Hoerling, M; Schubert, S; Wang, H; Lyon, B; Kumar, A; Nakamura, J; Henderson, N., Causes and predictability of the 2011-14 California Drought, NOAA Drought Task Force/NIDIS Assessment report, doi:10.7289/V58K771F.
https://cpo.noaa.gov/Meet-the-Divisions/Earth-System-Science-and-Modeling/MAPP/MAPP-Task-Forces/Drought/Drought-Task-Force-I/Causes-and-Predictability-of-the-2011-2014-

6. Seager, R. 2016: Physical mechanisms of the California drought. *Harvard Review of Environment and Society*,http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/Seager_HarvardRev2016SeagerOnly.pdf

7. Seager, R., N. Henderson, M.A. Cane, H. Liu and J. Nakamura, 2017: Is there a role for human-induced climate cChange in the precipitation decline that drove the California drought? J. Climate, 30: 10237-10258, DOI: 10.1175/JCLI-D-17-0192.1. http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/SeagerEtAl2017Human.pdf

8. Seager, R. and M. Ting, 2017: Decadal drought variability over North America: Mechanisms and predictability, Curr. Clim. Change Rep., DOI 10.1007/s40641-017-0062-1. http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/Seager_Ting_CCCR_2017.pdf

9. Seager, R. and N. Henderson, 2016: On the role of tropical ocean forcing of the persistent North American west coast ridge of winter 2013/14. J. Climate, 29, 8027-8049, DOI: 10.1175/JCLI-D-16-0145.1. https://journals.ametsoc.org/doi/10.1175/JCLI-D-16-0145.1

10. Williams, A. P., R. Seager, J. T. Abatzoglou, B. I. Cook, J. E. Smerdon and E. R. Cook, 2015: Contribution of anthropogenic warming to the 2012-14 California drought, *Geophys. Res. Lett.*, **42**, 68196828, 10.1002/2015GL063266. http://ocp.ldeo.columbia.edu/res/div/ocp/pub/seager/WilliamsEtAl_2015_GRL_CA_drought_SIsection.pdf

14. Presentations, seminars, visuals

- A tale of two droughts: California and Chile. Universidad de Austral de Chile, Valdivia, Chile, June 2017.
- The California drought, CalTech, January 2017.
- The California drought, Oxford University, U.K., October 2016.
- The California drought, U. Reading, U.K., October 2016.
- The monster El Niño of 2015/16: What was expected and what happened, the case of California, Columbia University, May 2016
- The physical causes of the California drought, NAS annual meeting, Washington DC, May 2016.
- The California drought, NCAR, April 2016.
- The causes of the California drought, AGU San Francisco, December 2015.
- The California drought, MIT, October 2015.
- The California drought, Grantham Institute, October 2015.
- The California drought, University of East Anglia, October 2015
- And now for something completely different: Causes of the California drought with an aside on the paleo-North American Monsoon, CalTech symposium on the monsoons, May 2015.
- A tale of three current droughts: California, Syria and East Africa, Workshop on Weather and Climate Extremes, Columbia University, May 2015
- A tale of three current droughts: California, Syria and East Africa, Workshop on Weather and Climate Extremes, Columbia University, May 2015.
- Mechanisms of future North America Hydroclimate Change, Yale University, March 2015.
- North American Hydroclimate variability over the last millennium, Yale University, March 2015.
- Causes and predictability of the 2011/14 California Drought, Bureau of Meteorology, Melbourne, Australia, February 2015.
- Improving seasonal climate prediction. Congressional staff briefing, Washington, DC, January 2015.
- Causes and predictability of the 2011/14 California Drought, NOAA Drought Task Force press conference, December 2014.
- Causes and predictability of the 2011/14 California Drought, Lamont Doherty Earth Observatory, November 2014.

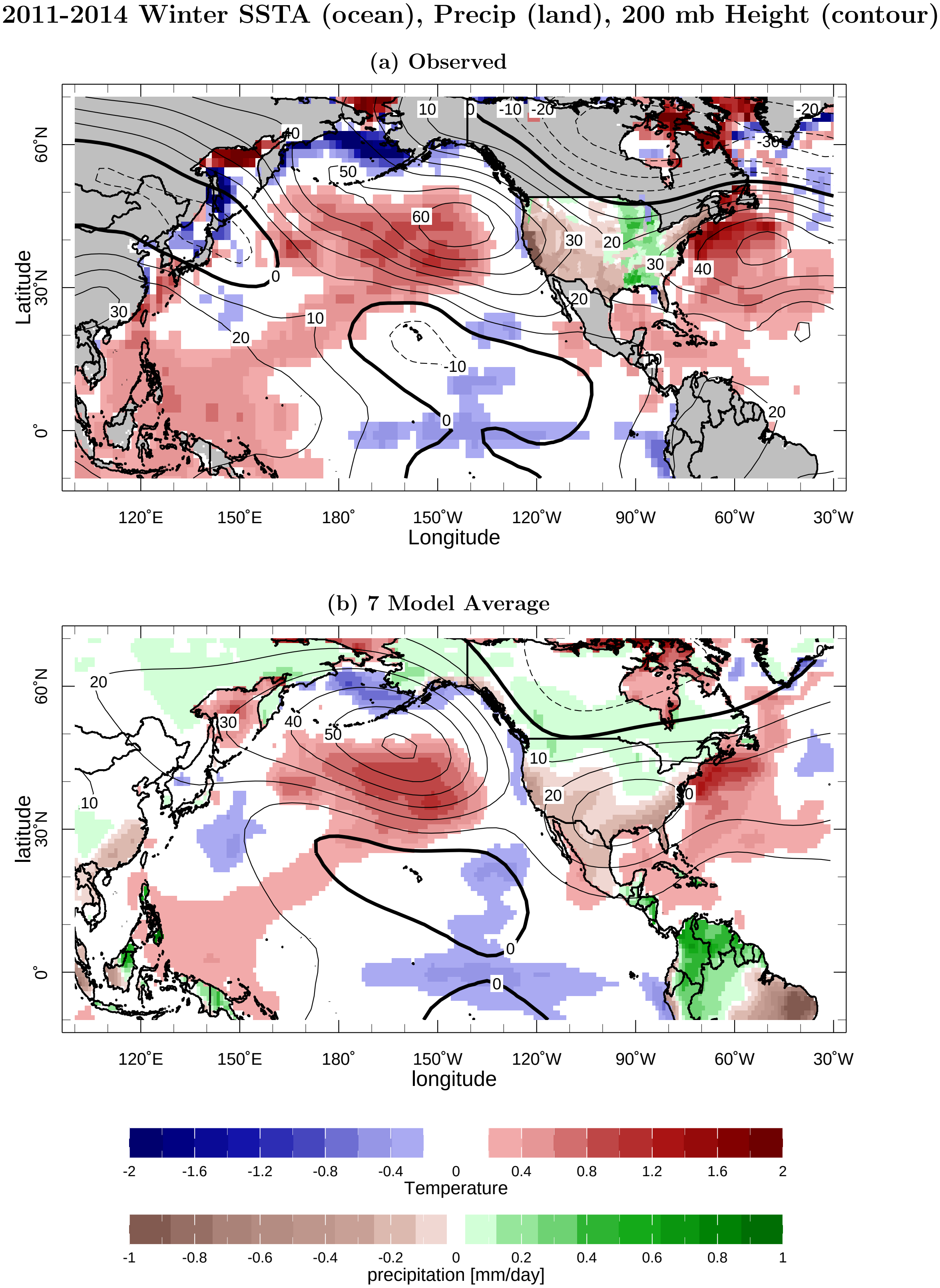

Figure 1: The observed (top) and seven model ensemble mean average (bottom) 200mb height anomalies (contours, m), SST (colors, ocean, K) and U.S. (top) or land (bottom) precipitation (colors, land, mm/day) anomalies averaged over the 2011/14 winter half years.

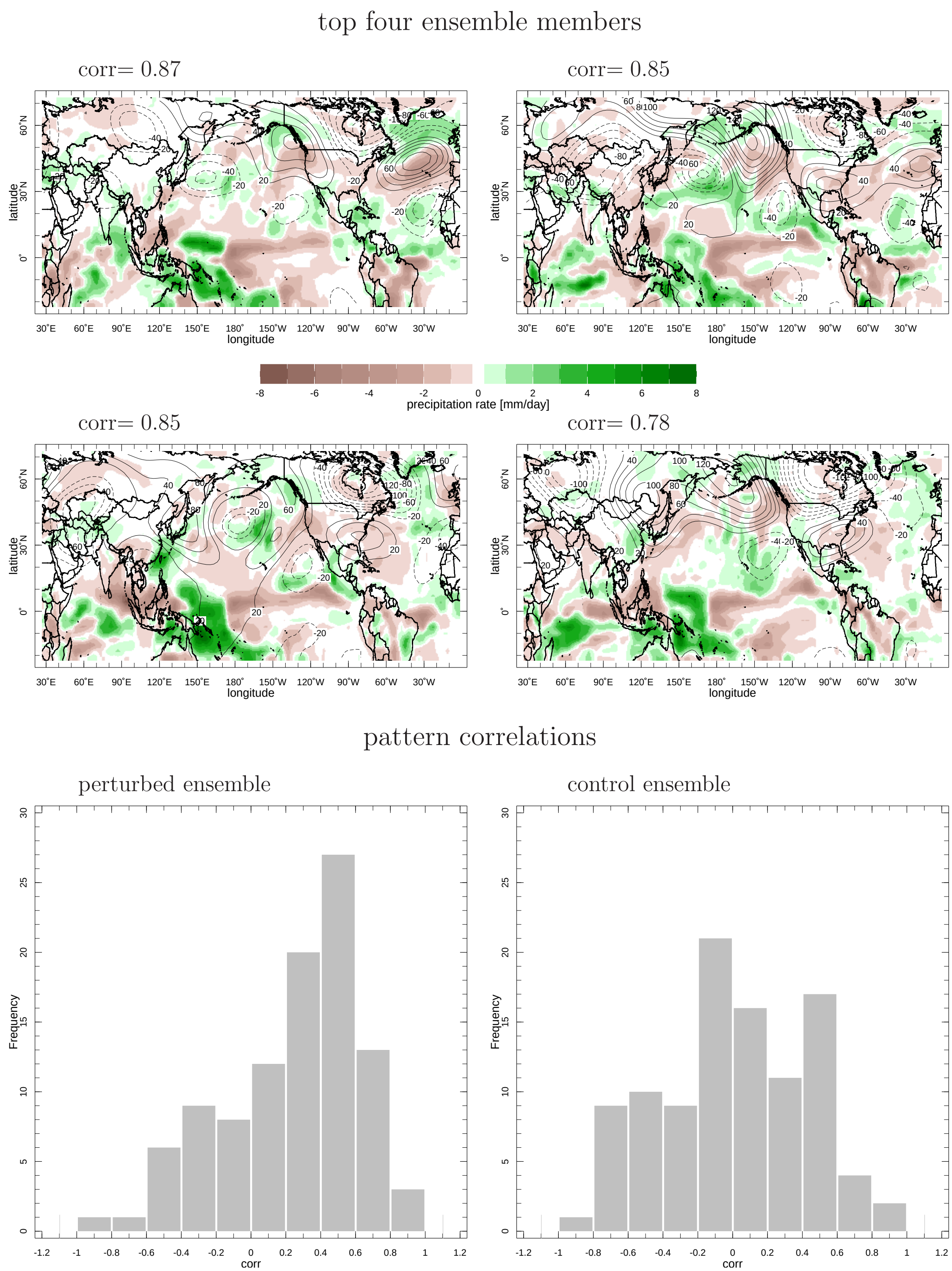

Figure 2: Results from 100 member ensemble simulations with imposed idealized SST anomalies. The target height field was that of winter 2013/14 and the linear combination of imposed SST anomaly experiments that best matches the target field was determined via optimization. The model was then rerun with the optimal SST anomaly configuration. The 200mb height and precipitation anomaly for the four optimal SST anomaly ensemble members that have the highest extratropical pattern correlation with the observed DJF 2013/14 height anomaly are shown as maps.. Units are m/s for heights and mm/day for precipitation. The distributions show the pattern correlations of all 100 ensemble members with the observed height field for the optimal SST anomaly ensemble (right) and a control ensemble with climatological SST (left). The presence of the SST anomaly notably warm in the tropical west Pacific.

15. Media coverage

The work on the California drought generated enormous media coverage, too much to list here but here are some examples.

https://www.nytimes.com/2014/12/09/science/earth/california-drought-is-said-to-have-natural-ca
html

https://www.washingtonpost.com/news/capital-weather-gang/wp/2014/12/08/noaa-report-says-califo
?noredirect=on&utm_term=.e3b1bb3e1ee4

https://www.nbcnews.com/science/environment/global-warming-isnt-causing-california-drought-rep

https://news.nationalgeographic.com/news/2014/12/141208-california-drought-causes-global-warmi

https://www.agweb.com/article/california-drought-more-natural-than-man-made-study-finds-blmg/

https://www.motherjones.com/environment/2014/12/new-study-californias-epic-drought-probably-wa

https://apnews.com/b37473a8bfb0468a8cafc663a626ea66

https://www.bloomberg.com/news/articles/2014-12-08/california-drought-more-natural-than-man-ma

https://www.sacbee.com/news/state/california/water-and-drought/article31679366.html